The Temperature and Cooling Age of the White-Dwarf Companion to the Millisecond Pulsar PSR B1855+09

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ABSTRACT

We report on Keck and *Hubble Space Telescope* observations of the binary millisecond pulsar PSR B1855+09. We detect its white-dwarf companion and measure $m_{\rm F555W} = 25.90 \pm 0.12$ and $m_{\rm F814W} = 24.19 \pm 0.11$ (Vega system). From the reddening-corrected color, $(m_{\rm F555W} - m_{\rm F814W})_0 = 1.06 \pm 0.21$, we infer a temperature $T_{\rm eff} = 4800 \pm 800\,{\rm K}$. The white-dwarf mass is known accurately from measurements of the Shapiro delay of the pulsar signal, $M_{\rm C} = 0.258^{+0.028}_{-0.016}\,M_\odot$. Hence, given a cooling model, one can use the measured temperature to determine the cooling age. The main uncertainty in the cooling models for such low-mass white dwarfs is the amount of residual nuclear burning, which is set by the thickness of the hydrogen layer surrounding the helium core. From the properties of similar systems, it has been inferred that helium white dwarfs form with thick hydrogen layers, with mass $\gtrsim 3 \times 10^{-3}\,M_\odot$, which leads to significant additional heating. This is consistent with expectations from simple evolutionary models of the preceding binary evolution. For PSR B1855+09, though, such models lead to a cooling age of $\sim 10\,{\rm Gyr}$, which is twice the spin-down age of the pulsar. It could be that the spin-down age were incorrect, which would call the standard vacuum dipole braking model into question. For two other pulsar companions, however, ages well over 10 Gyr are inferred, indicating that the problem may lie with the cooling models. There is no age discrepancy for models in which the white dwarfs are formed with thinner hydrogen layers ($\lesssim 3 \times 10^{-4}\,M_\odot$).

Subject headings: binaries: general — pulsars: individual (PSR B1855+09) — stars: evolution — white dwarfs

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1. Introduction

About one twentieth of the known radio pulsars reside in binary systems. For most of these, the companions have estimated masses between 0.1 and $0.4\,M_\odot$ and are thought to be low-mass, helium white dwarfs. Generally, the properties of the pulsars in these systems differ markedly from those of typical isolated pulsars, showing more rapid spin periods and smaller inferred magnetic fields (for reviews, see, e.g., Phinney & Kulkarni 1994; Van den Heuvel 1995). Presumably, this is because of a phase of mass and angular momentum transfer which occurred when the progenitor of the current white dwarf ascended on the giant branch and overfilled its Roche lobe. At the cessation of mass transfer, the neutron star turned on as a millisecond radio pulsar and the companion was left as a helium white dwarf.

An interesting property of these binaries is that they contain two independent clocks that started running more or less simultaneously: the spin-down age of the pulsar and the cooling age of the white dwarf (Kulkarni 1986). Assuming that the pulsar spins down due to a torque $N \propto \nu^n$, the pulsar age is given by

$$t_{\rm PSR} = \frac{P}{(n-1)\dot{P}}\left[1 - \left(\frac{P_0}{P}\right)^{n-1}\right], \qquad (1)$$

where $P \equiv 1/\nu$ is the current spin period, $\dot{P}$ is its rate of change, P_0 is the period when the pulsar began spinning down following cessation of mass transfer, and $n = \nu\ddot{\nu}/\dot{\nu}^2$ is the "braking index," equal to 3 under the assumption of magnetic dipole radiation (for a review, see Lyne & Smith 1998). For $n = 3$ and $P_0 \ll P$, $t_{\rm PSR} \simeq \tau_{\rm c} \equiv P/2\dot{P}$, where $\tau_{\rm c}$ is the pulsar "characteristic age."

The cooling age of the white dwarf, the second clock, can be determined from the stellar temperature and mass using a cooling model. The cooling properties of helium white dwarfs have been modeled extensively, particularly since the optical identification of a number of white-dwarf companions of millisecond pulsars. A central issue that has arisen is how much hydrogen remains when the white dwarf is formed. Most likely, the amount of hydrogen left will be anti-correlated with core mass, since for larger core masses the pressure at the core-envelope interface required for CNO cycle shell burning can be maintained down to lower envelope masses. If a white dwarf is left with a sufficiently thick remaining hydrogen layer, with mass $\gtrsim 10^{-3}\,M_\odot$, residual nuclear burning in the p-p cycle will be a significant source of heat during the further evolution, and, for a given age, the white dwarf will be hotter than one whose hydrogen layer is thinner.

Evidence in favor of thick hydrogen layers and significant nuclear burning comes from the millisecond pulsar binary system PSR J1012+5307. For this binary, $t_{\rm PSR} \simeq 7\,$Gyr (Lorimer et al. 1995), while from the surface temperature and gravity, as determined using optical spectroscopy ($T_{\rm eff} \simeq 8500\,$K, $\log g \simeq 6.7$; Van Kerkwijk, Bergeron, & Kulkarni 1996; Callanan, Garnavich, & Koester 1998), one infers a much shorter cooling age, $t_{\rm WD} \simeq 0.5\,$Gyr, if one uses models in which the white dwarf is assumed to have formed with a relatively thin hydrogen layer ($\lesssim 3 \times 10^{-4}\,M_\odot$), with, in consequence, little nuclear burning (Lorimer et al. 1995; Sarna, Marks, & Connon Smith 1996; Althaus & Benvenuto 1997; Hansen & Phinney 1998). It has been argued that this implies that the pulsar has not yet spun down much, i.e., $P_0 \simeq P$. Alberts, Savonije, & Van den Heuvel (1996) and Driebe et al. (1998), however, find from simple evolutionary models in which the mass loss during the red giant phase is simulated, that the helium white dwarf companion should have had a much thicker hydrogen layer at formation, $\sim 5 \times 10^{-3}\,M_\odot$. With this thicker layer, they obtain a cooling age that is consistent with the pulsar spin-down age.

The results are less clear for other systems with optically identified companions, since these are too faint for optical spectroscopy and their masses can only be estimated from the mass function (using a guess for the pulsar mass and statistical arguments for the orbital inclination). There is one system, however, for which the mass of the white dwarf is known precisely. This system is PSR B1855+09, composed of a 5.4 ms radio pulsar and a low-mass companion in a 12.3 d circular orbit (Segelstein et al. 1986). The pulsar is a very stable rotator and it has been possible to measure the general relativistic Shapiro delay of the pulsar signal near superior conjunction (Ryba & Taylor 1991; Kaspi, Taylor, & Ryba 1994). From the measurements, one infers that the binary is nearly edge on ($\sin i = 0.9992^{+0.0004}_{-0.0007}$) and that the companion has mass $M_{\rm C} = 0.258^{+0.028}_{-0.016}\,M_\odot$. In addition, from the measured parallax, $\pi = 1.1 \pm 0.3\,$mas, the distance is $0.91^{+0.35}_{-0.20}\,$kpc. The characteristic age $\tau_{\rm c}$ of the pulsar is 5 Gyr. Optical observations of the field have so far failed to detect the companion, but set stringent

limits, showing that it must be an old, cold white dwarf (Callanan et al. 1989; Kulkarni, Djorgovski, & Klemola 1991).

Here, we report on Keck and *Hubble Space Telescope* observations of the PSR B1855+09 field, in which the counterpart is detected. We use these to determine the effective temperature and discuss the implications for cooling of helium white dwarfs and braking of millisecond pulsars.

2. Observations

The PSR B1855+09 field was observed on 10 August 1994 using the Low-Resolution Imaging Spectrometer (Oke et al. 1995) on the 10 m Keck telescope. Dithered exposures were taken with total integration times of 40 minutes in R and 33 minutes in I. The conditions were good, with seeing of $\sim 0.''8$ in I and $\sim 1.''1$ in R. These images showed a faint object at the pulsar position, but because the field is very crowded, it was not clear whether or not the object was the result of a blend, and its magnitude was difficult to determine.

Therefore, the Wide Field Planetary Camera 2 aboard the *Hubble Space Telescope* was used to observe the PSR B1855+09 field for one orbit each on 6 August 1997 and 19 February 1998. The first observation consisted of three 700 s exposures through the F555W filter (mean wavelength $\bar{\lambda} = 5397$ Å, effetive width $\Delta\lambda = 1226$ Å; Holtzman et al. 1995a), the second of five 260 s exposures through F814W ($\bar{\lambda} = 7924$ Å, $\Delta\lambda = 1500$ Å). The field around the pulsar was put on a clean spot on the CCD of the Planetary Camera (PC). Only the PC images are used here.

For both data sets, the images were registered to half-pixel accuracy and resampled using pixels with half the original size. Next, cosmic ray hits were identified by comparing values at a given position with the minimum value occurring among the images at that position. A stacked image was formed using all unaffected pixels, and this image was resampled to the original pixel scale for the further analysis. The stacked images are presented in Figure 1.

Astrometry was done relative to the USNO-A2.0 catalog (Monet et al. 1998), using only those 189 objects that were not overexposed in a 10 s I-band Keck image and that appeared stellar and unblended. We measured their centroids and corrected for instrumental distortion using a bi-cubic function determined by J. Cohen (1995, private communication). Next, we fitted for zero-point position and position angle on the sky, keeping the plate scale at the known value. Rejecting 28 outliers (residuals $> 1''$), the inferred single-star measurement error is $0.''33$ in each coordinate. This is somewhat larger than we have found for other fields (e.g., Van Kerkwijk & Kulkarni 1999), probably because in this crowded field there are residual problems with blending in the USNO-A2.0 positions.

The solution was transferred to the F555W and F814W PC frames using 50 and 54 transfer stars, respectively. For these, the PC positions were corrected for instrumental distortion using the bi-cubic function given by Holtzman et al. (1995b). We fitted for the zero-point position only, as the plate scale and position angle on the sky are known accurately (see Holtzman et al. 1995b). Rejecting four and three outliers for F555W and F814W, respectively (residuals $> 0.''08$), the inferred single-star measurement errors for both are $0.''027$ in each coordinate[5].

The main uncertainty in our astrometric solution is the extent to which the timing position of PSR B1855+09 and the USNO-A2.0 catalog are on the same astrometric system. The former is based on the DE200 dynamical ephemeris and should be close to the International Celestial Reference System (ICRS; Folkner et al. 1994). The USNO-A2.0 catalog is tied to the ICRS as well (see Monet et al. 1998). There may be small systematic differences, however, as well as effects of the average proper motion of the USNO-A2.0 stars between the plate epoch (~ 1954) and the time of our Keck observation (1994.6) due to Galactic rotation, asymmetric drift, and reflex of the solar motion.

We tried to measure the offset of our solution from the ICRS using two Hipparcos (ESA 1997) stars, HIP 93083 and HIP 93084, which are on our 10 s I-band image. These stars are strongly overexposed, but nonetheless we were able to determine good centroids by fitting all unaffected pixels, with different fitting methods agreeing to within $0.''03$. The offsets in both right ascension and declination between the positions inferred from our solution and the two Hipparcos stars (at epoch 1994.6) were consistent to within $0.''04$ (0.02 pix), the averages being $0.''17 \pm 0.''05$ and $0.''34 \pm 0.''05$, respectively.

For verification, we took 20 AGN with VLBI-ICRS

[5]Leaving scale and position angle free, this reduces to $0.''014$. The final position, however, changes by $< 0.''006$.

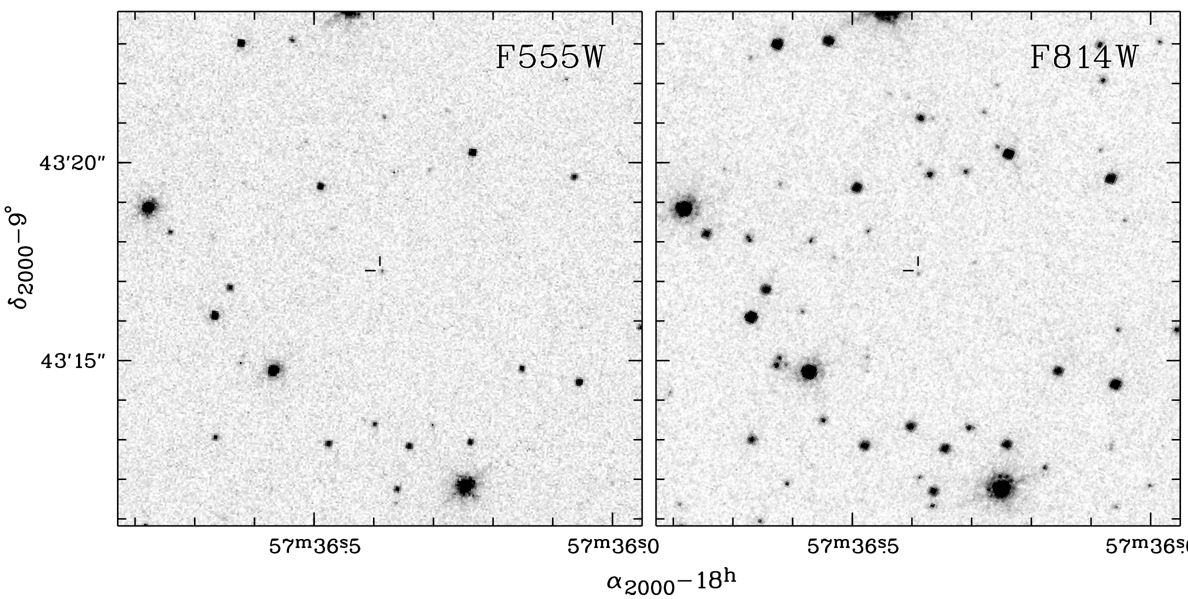

Fig. 1.— *HST* images of the PSR B1855+09 field, taken through the F555W (left) and F814W (right) filters. The epoch 1998.0 timing position is shown by the tick marks. These are 0.″24 long, equal to the 95% confidence diameter inferred from the uncertainty in the astrometric tie.

positions within 45° of PSR B1855+09 from the list of Ma et al. (1998) and measured the positions of their optical counterparts on the second Digitized Sky Survey (epoch ~ 1991), with astrometry tied to USNO-A2.0 (epoch ~ 1954). We find average offsets consistent with the above, of $0.''18 \pm 0.''04$ and $0.''28 \pm 0.''04$ (the average offsets between the VLBI and the USNO-A2.0 positions are 0.″09 and 0.″11; the additional difference is consistent with what is expected from the average proper motion of reference stars at ~ 2 kpc). We conclude that, after correction for the offset found using the Hipparcos stars, our astrometry should be on the ICRS to 0.″05.

Near the position of PSR B1855+09 – $\alpha_{\rm J2000} = 18^{\rm h}57^{\rm m}36.^{\rm s}3917$, $\delta_{\rm J2000} = 09°43'17.''275$ at epoch 1998.0 (Kaspi, Taylor, & Ryba 1994) – the PC images show one object. It is offset by $-0.''01 \pm 0.''05$ and $-0.''04 \pm 0.''05$ in right ascension and declination, respectively (see Fig. 1). Given the density of objects of about 1 per three square arcseconds, the probability of a chance coincidence in our 0.″12 radius 95% confidence error circle is $\sim 1.5\%$. Thus, most likely we have detected the counterpart of PSR B1855+09.

Photometry of the object was done following the prescription of Holtzman et al. (1995a). We performed aperture photometry for a range of different radii, and used some two dozen brighter stars in the frame to determine aperture corrections relative to the standard 0.″5 (11 pix) radius aperture. For the candidate, the best signal-to-noise ratio is for relatively small apertures, with radii between 1.5 and 3 pix. From these, we infer a count rate for the 0.″5 radius aperture of 0.042 ± 0.005 and $0.087 \pm 0.009\,{\rm DN\,s^{-1}}$ for the F555W and F814W filters, respectively (1 DN is approximately 7 detected photons; Holtzman et al. 1995a). These count rates correspond to magnitudes of $m_{\rm F555W} = 25.90 \pm 0.12$ and $m_{\rm F814W} = 24.19 \pm 0.11$ in the Vega system (using $m_{\rm F555W} = 22.545$ and $m_{\rm F814W} = 21.639$ for a count rate of $1\,{\rm DN\,s^{-1}}$ in the PC, and applying a 0.10 mag aperture correction from 0.″5 radius to "nominal infinity"; Baggett et al. 1997).

3. Discussion

The temperature of the white dwarf can be constrained using the measured color, $m_{\rm F555W} - m_{\rm F814W} = 1.71 \pm 0.16$. For this purpose, we correct for reddening using the estimate $E_{B-V} = 0.5 \pm 0.1$ of Kulkarni et al. (1991). This estimate is based on CO emission and H I 21-cm absorption measurements towards PSR B1855+09 and is consistent with the range 0.5–0.7 estimated in the general direction of PSR B1855+09 from reddening of O–F stars

(Neckel, Klare, & Sarcander 1980). The redding corresponds to $A_{\rm F555W} = 1.6 \pm 0.3$ and $E_{\rm F555W-F814W} = 0.65 \pm 0.13$ (Schlegel, Finkbeiner & Davis 1998), and we infer $(m_{\rm F555W} - m_{\rm F814W})_0 = 1.06 \pm 0.21$. This intrinsic color corresponds to $T_{\rm eff} = 4800 \pm 800\,{\rm K}$ if the atmosphere were pure hydrogen (Bergeron, Saumon, & Wesemael 1995; using the color transformations of Holtzman et al. 1995a), but could be lower than 4000 K for a mixed helium/hydrogen atmosphere. (Note that the surface gravity expected for the companion, $\log g \simeq 7.2$, is outside the range 7.5–8.5 covered by the atmospheric models of Bergeron et al. [1995], and thus we had to extrapolate; the colors, however, are not very sensitive to $\log g$.)

A consistency check on the estimated temperature is available using the absolute magnitude. From the measured white dwarf mass ($M_{\rm C} = 0.258^{+0.028}_{-0.016} M_\odot$; Kaspi, Taylor, & Ryba 1994), we infer a radius $R_{\rm C} = 0.021 R_\odot$ (using the models of Driebe et al. [1998]; the result is not sensitive to model details). Combined with our estimate of $T_{\rm eff}$, one infers $M_{\rm bol} \simeq 13.9$, and, using bolometric corrections tabulated by Bergeron et al. (1995), $M_{\rm F555W} \simeq 14.3$. Correcting for reddening, this corresponds to a parallax of 1.0 mas, consistent with the timing parallax of 1.1 ± 0.3 mas.

With $T_{\rm eff}$ and $M_{\rm C}$, the cooling age of the white dwarf can be estimated using a cooling model. As discussed in § 1, the main uncertainty in the models is the amount of nuclear burning, which is set by the thickness of the hydrogen layer surrounding the helium core. Generally, hydrogen layers have been assumed to be relatively thin, and little account has been taken of a possible dependence on stellar mass. For instance, Hansen & Phinney (1998) modeled helium white dwarfs having hydrogen layers of $3 \times 10^{-4} M_\odot$ and $10^{-6} M_\odot$. With their models, one infers a cooling age for the white dwarf here of $\sim$3 Gyr. Using simple evolutionary models for the progenitor of the white dwarf, however, much thicker layers are found; e.g., for a $1\,M_\odot$ progenitor that ends up as a $0.259\,M_\odot$ white dwarf, Driebe et al. (1998) find a hydrogen layer of $4.8 \times 10^{-3} M_\odot$ at formation. With this much thicker layer, nuclear burning is much more important, and the cooling age becomes much longer, $t_{\rm WD} = 10 \pm 2$ Gyr (by which time only $\sim 0.7 \times 10^{-3}\,M_\odot$ of hydrogen is left).

The white dwarf age inferred from the Driebe et al. model is greater than the characteristic age of the pulsar, $\tau_{\rm c} = 5$ Gyr. If the model were correct, $\tau_{\rm c}$ must be an underestimate of the true age of the PSR B1855+09 system. One interpretation is that the braking index of this millisecond pulsar is less than the canonical value of 3; to obtain $t_{\rm PSR} > 8$ Gyr would require $n < 2.25$ (Eq. 1). This is perhaps not unreasonable, as for most pulsars for which braking indices have been measured, values less than 3 have been found: $n = 2.51 \pm 0.01$ for PSR B0531+21 (Lyne, Pritchard, & Smith 1993); 2.28 ± 0.02 for PSR B0540−69 (Boyd et al. 1995); 1.4 ± 0.2 for PSR B0833−45 (Lyne et al. 1996); and 2.837 ± 0.001 for PSR B1509−58 (Kaspi et al. 1994). All these pulsars, however, are young and have strong magnetic fields, so their relevance to the discussion here is not clear. We note that a variant on the vacuum-dipole model (Melatos 1997), which does a reasonable job of explaining these braking indices, predicts $n = 3$ for a pulsar like PSR B1855+09 (A. Melatos & J. Hibschman, 1999, private communication).

The optical counterparts of other pulsar binaries may give a clue to where the problem lies. From the list compiled by Hansen & Phinney (1998), we find that two pulsars, PSRs J0034−0534 and J1713+0747, have very cool companions, with $T_{\rm eff} < 3500$ K and $T_{\rm eff} = 3400 \pm 300$ K, respectively. For such temperatures, the cooling ages inferred from the models of Driebe et al. (1998) are well over 10 Gyr, even if the orbital inclinations were such that the helium white dwarfs had close to the maximum mass[6]. While these ages are not inconsistent with the estimated pulsar ages, they exceed estimates of the age of the Galaxy from the white-dwarf luminosity function (for recent determinations, see Leggett, Ruiz, & Bergeron 1998; Knox, Hawkins, & Hambly 1999). This suggests that the models may overestimate the cooling ages.

The above is in contrast to what is the case for PSR J1012+5307, where the cooling age estimated using the Driebe et al. model is very similar to $\tau_{\rm c}$ (§ 1). The discrepancy might be resolved by the thickness of the hydrogen layer being a function of the orbital separation, perhaps via somewhat different mass-loss histories. PSR J1012+5307 has the second-shortest orbital period of all systems known (0.6 d), much shorter than that of PSR B1855+09 (12.3 d). PSR J0034−0534, however, discussed above as an-

[6]The companion of PSR J0034−0534 could also be a CO white dwarf, which would make the cooling age much shorter (Schönberner, Driebe, & Blöcker 1999). The required low orbital inclination has $\sim$10% a priori likelihood. The companion of PSR J1713 has mass $0.27 < M_{\rm C} < 0.4\,M_\odot$ and thus should be a helium white dwarf (Camilo, Foster, & Wolszczan 1994).

other case for which thick hydrogen layers may be problematic, has a short orbital period (1.6 d).

The discrepancy might also result from differences in white-dwarf mass. For instance, Driebe et al. (1999) find that shell flashes only occur in a limited range of masses (0.21–0.30 $M_{\odot}$), which includes PSR B1855+09 but not PSR J1012+5307. Driebe et al. found that burning during the flashes does not greatly affect the cooling ages. Schönberner, Driebe, & Blöcker (1999), however, in duscussing our result, have suggested that envelope expansion during and following a flash could cause Roche-lobe overflow. The resulting mass transfer to the pulsar (which might temporarily become an X-ray source again) could lead to a thinner hydrogen layer. If so, then with stronger constraints on companion masses, as can be derived for PSR J1713+0747 in particular, the mass range in which shell flashes occur can be constrained observationally.

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